

Cosmic Reionization and Galaxy Formation

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Abstract. Using 3D radiative transfer calculations on the reionization of an inhomogeneous universe, QSO absorption line systems are simulated and they are compared with observations of Ly α continuum depression at high redshifts. By this comparison, it is found that the metagalactic UV intensity decreases rapidly with z at $z > 4$ as $I_{21} = 0.5 \exp[3(4 - z)]$, and the reionization must have taken place between $z = 6$ and 10. Based on this time-dependence of UV background intensity, we explore the collapse of pregalactic clouds in the UV background, and find that the self-shielding is prominent above a mass scale as $M_{\text{BIF}} = 3.0 \times 10^{11} M_{\odot} [(1 + z_c)/5]^{-4.2} (I_{21}/0.5)^{0.6}$. This mass scale predicts the bifurcation of galactic morphology, and by confrontation with observations it turns out that the bifurcation mass successfully discriminates between elliptical and spiral galaxies.

1. Introduction

The cosmic reionization is an issue of great significance in cosmology in relation to the formation of galaxies. The information on the ionization states has been accumulated by the observations of Ly α absorption lines in high redshift QSO or galaxy spectra. Recently, 3D cosmological hydrodynamic simulations (Cen et al. 1994; Miralda-Escude et al. 1996; Gnedin & Ostriker 1996; Zhang et al. 1997) have revealed that the Ly α absorption systems can be explained in terms of the absorption by intergalactic density fluctuations. Also, the radiative transfer effects have been stressed by 3D calculations on the reionization of intergalactic matter (Abel, Norman, & Madau 1999; Razoumov & Scott 1999; Gnedin 2000; Nakamoto, Umemura, & Susa 2000; Ciardi et al. 2000). Here, to elucidate the reionization history, we simulate QSO absorption lines by using the results of 3D radiative transfer calculations and compare them to observations at high redshifts. Also, the collapse of pregalactic clouds in a reionized universe is explored in relation to the formation of protogalaxies in UV background radiation.

2. QSO Absorption Lines at High Redshifts

2.1. Ly α Continuum Depression and Reionization History

In a simulation box, random Gaussian density fluctuations are generated based upon the Zel'dovich approximation in the context of CDM cosmology. The

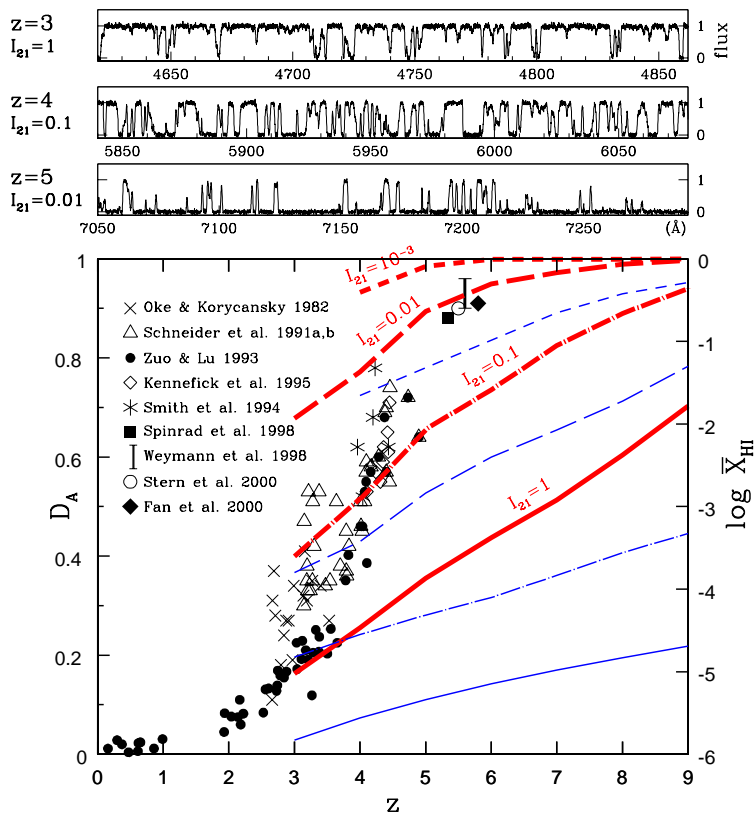


Figure 1. The simulated Ly α absorption lines against wavelength at $z = 3$ (*top panel*) with $I_{21} = 1$, $z = 4$ (*second*) with $I_{21} = 0.1$, and $z = 5$ (*third*) with $I_{21} = 0.01$. The bottom panel is the diagram of Ly α continuum depression (*thick gray curves*) against redshifts. Symbols are observations. Also, the mean neutral fractions \bar{X}_{HI} (*thin curves*) are shown. The same line type corresponds to the same UV intensity.

simulation box is irradiated by the isotropic UV background radiation of a power law-type spectrum, $I_\nu = I_{21} 10^{-21} (\nu_L/\nu) \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$, where ν_L is the Lyman limit frequency. The ionization structure is obtained by solving the three-dimensional radiative transfer equation. The details of numerical techniques are presented in Nakamoto, Umemura, & Susa (2000) (see also the paper by Nakamoto et al. in this volume).

The resultant ionization degrees in the universe are different from place to place by more than three orders of magnitude. Due to such inhomogeneous ionization structure, relatively low ionization regions could produce strong absorption in quasar spectra. To make a direct comparison with the observations, we simulate absorption lines. First, we focus on Ly α absorption. To match the recent observations by the Keck telescope, we adopt the resolution of $R=45000$ and the variance of 0.04, and assume the Voigt profile of lines. The simulated Ly α absorption features are shown in upper three panels in Figure 1.

In order to compare the simulated absorption degree with observations, we have assessed the so-called continuum depression, D_A . In Figure 1, the simulated D_A is compared to observations at high redshifts. We see that any model with a constant UV intensity does not match the observed trend that D_A tends to grow quickly at redshifts higher than 4. This implies that the metagalactic UV intensity must decrease rapidly with z at $z > 4$ by two orders of magnitude at least. The redshift dependence of UV background is required to be $I_{21} = 0.5 \exp[3(4 - z)]$ at $z > 4$. If the UV intensity decreases in this fashion, the reionization epoch is estimated to be $z \approx 6$. If the intensity keeps a level of $I_{21} = 0.01$ at $z > 5$, the reionization epoch is assessed to be $z \approx 9$.

Thus, it is concluded that the cosmic reionization must have taken place between $z = 6$ and 10. However, the Ly α absorption is not appropriate to determine the reionization epoch more accurately, because, as seen in the absorption features in Figure 1, Ly α is too strongly depleted even if the mean neutral fraction is less than 10^{-2} . In other words, D_A is no longer sensitive to X_{HI} around the cosmic reionization epoch.

2.2. H α Forest

As shown in the previous subsection, Ly α has too high line opacity to probe the universe at $z > 5$. Therefore, three conditions are required for a line in order to investigate the universe at $z > 5$: (1) it has lower line opacity than Ly α , (2) line emission is detectable, and (3) it has lower extinction against dust because young star-forming galaxies are often dust-enshrouded. The most favorable solution seems to be H α absorption lines. The H α absorption is likely to be relatively weak around $z = 3$, while it could be sensitive to the ionization degrees at $z > 4$. Therefore, H α forest can be a more powerful tool to probe the universe at $z > 5$. H α forest has been never detected so far. The reason comes from the fact that H α has much weaker opacity than Ly α . From observational points of view, the H α continuum depression can be detected by low-dispersion spectroscopy or narrow-band photometry. Furthermore, H α forest is subject to less UV bump effects for AGNs compared to Ly α forest. The wavelengths of H α forest drop on $3\mu\text{m} \lesssim \lambda_{H\alpha} \lesssim 7\mu\text{m}$ at $4 \lesssim z \lesssim 10$. Thus, the observations can be done with Subaru IRCS, IRIS, SIRTf, NGST, or H2/L2. If one can obtain the absorption features with the resolution greater than 10000, one can recover the density fluctuations at high redshifts. They allow us to determine the linear amplitude of pregalactic perturbations which is by no means measured in the CBR due to the strong Sunyaev-Zeldovich effects in galactic scales. If one has the amplitude of linear density fluctuations at galactic scales, one can not only set the initial condition for galaxy formation, but also make more reliable determination of cosmological parameters.

3. Galaxy Formation in UV Background Radiation

3.1. Bifurcation Theory

Here, the cosmology is assumed to have $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, and $\Omega_b h^2 = 0.02$ with usual meanings. Susa & Umemura (2000a) have explored the sheet collapse of a pregalactic cloud under UV background radiation, with

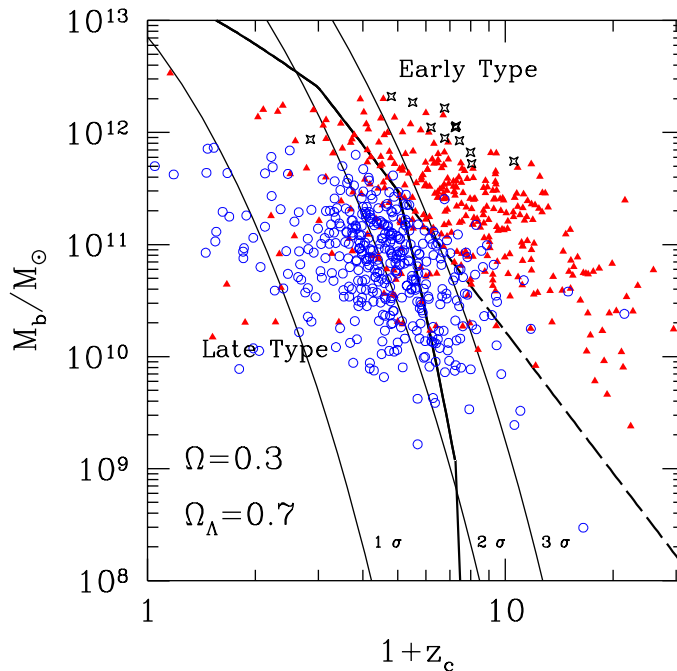


Figure 2. Confrontation of the bifurcation theory to observations. The thick solid and dashed lines represent the bifurcation mass M_{BIF} , respectively for model A and B. Small open circles represent spiral galaxies. Small filled triangles denote the E and E-S0 galaxies, and open stars are massive elliptical galaxies from X-ray observations. Three thin solid lines marked as 1σ , 2σ , and 3σ are density fluctuations in the CDM cosmology.

including H_2 chemistry. They have found that the cloud evolution is specified by two initial parameters, i.e., the mean density (\bar{n}_{ini}) and the thickness (λ). The initial parameter dependence is translated into the baryonic mass [$M_b \equiv (4\pi/3)\bar{n}_{\text{ini}}(\lambda/2)^3$] and the collapse epoch (z_c) by assuming the initial stage is close to the maximum expansion of a density fluctuation. The numerical results have shown that the cloud evolution bifurcates into two characteristic states, i.e., (a) a pregalactic cloud is self-shielded against the external UV in the course of the sheet collapse, so that the cloud cools down below 10^3K due to H_2 cooling and undergoes efficient star formation. Hence, it is expected to evolve into an early type galaxy with a high bulge-to-disk ratio (B/D) due to the dissipationless virialization, or (b) a cloud is not self-shielded during the sheet collapse, but is self-shielded through the shrink to the rotation barrier. This leads to the retarded star formation, and thus the virialization would proceed in

a fairly dissipative fashion. As a result, a late type (small B/D) galaxy would be preferentially born. Such bifurcation is specified solely by a mass scale as

$$M_{\text{BIF}} = 3.0 \times 10^{11} M_{\odot} \left(\frac{1+z_c}{5} \right)^{-4.2} \left(\frac{I_{21}}{0.5} \right)^{0.6}, \quad (1)$$

where z_c is the collapse epoch and I_{21} is the UV background intensity in units of $10^{-21} \text{erg s}^{-1} \text{cm}^{-2} \text{str}^{-1} \text{Hz}^{-1}$.

3.2. Confrontation with Observations

Here we include the effect of the evolution of UV background radiation. We assume $I_{21} = 0.5 [(1+z)/3]^3$ for $z \leq 2$ and $I_{21} = 0.5$ for $2 < z \leq 4$. This dependence is consistent with the UV intensity in the present epoch (Maloney 1993; Dove & Shull 1994), and the value inferred from the QSO proximity effects at intermediate redshifts (Bajtlik, Duncan, & Ostriker 1988; Giallongo et al. 1996). As for $z > 4$, two models are employed. The first one is (A) the exponentially damping model, $I_{21} = 0.5 \exp[3(4-z)]$, which is inferred by the continuum depression, and the second one is (B) the constant extrapolation model, $I_{21} = 0.5$.

Then, based upon the above paradigm of the galaxy formation under UV background, the evolutionary bifurcation of pregalactic clouds is confronted with observations of elliptical and spiral galaxies. Using the observed properties of galaxies, the collapse epochs are assessed for each type of galaxies with attentive mass estimation (Susa & Umemura 2000b). The comparison of observed galaxies with the bifurcation theory is presented in Figure 2. Small open circles represent spiral galaxies in Persic & Salucci (1995). Small filled triangles denote the E and E-S0 galaxies in Faber et al. (1989). Open stars are elliptical galaxies from X-ray observations in Matsumoto et al. (1997). The thick solid and dashed lines represent the bifurcation mass M_{BIF} , respectively for model A and B, where both are identical at $z_c < 4$. By this direct comparison of the theory with the observations, it turns out that the theoretical bifurcation branch successfully discriminates between elliptical and spiral galaxies. This suggests that the UV background radiation could play a profound role for the differentiation of the galactic morphology into the Hubble sequence. In Figure 2, the density fluctuations in the CDM cosmology are also plotted by three thin solid lines marked as 1σ , 2σ , and 3σ , where σ is the variance of CDM perturbations. We find that the bifurcation mass scale coincides with the $(2-3)\sigma$ density fluctuations. Thus, the present results are also intriguing from a view point of the density morphology relation of galaxies, because higher σ peaks reside preferentially in denser regions rather than in low-dense regions.

4. Conclusions

Using the ionization structure in an inhomogeneous universe obtained by 3D radiative transfer calculations on the reionization, we have simulated QSO absorption lines at high redshifts. By comparison of simulated $\text{Ly}\alpha$ continuum depression with recent observations, it has been found that the metagalactic UV intensity must decrease rapidly with z at $z > 4$, and the reionization must

have taken place between $z = 6$ and 10. Based on this time-dependence of UV background intensity, we have explored the collapse of pregalactic clouds in the UV background, and found that the degree of self-shielding bifurcates the evolution of protogalaxies. The bifurcation is characterized by a mass scale dependent on UV background intensity and redshift. By confrontation with observations it has turned out that the bifurcation mass successfully discriminates between elliptical and spiral galaxies. This suggests that the UV background radiation is closely related to the final bulge-to-disk ratios of galaxies.

We have assumed here AGN-like ionizing sources, but which type of sources reionized the universe is still an issue under a lot of debate. Anyhow, the present analysis suggests that to elucidate precisely the reionization history is extraordinarily important for the understanding of galaxy formation.

Acknowledgments. The numerical analysis has been made with computational facilities at Center for Computational Physics in University of Tsukuba.

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